specific application one should consider what starting crack size is consistent with the inspection, whether a rapid starting crack is natural to regions which might produce it, the possible tensile loads, the dimensional factors which pertain to elastic constraint, and the degree of precision necessary from the results of crack-toughness evaluation. When a high degree of precision is wanted, a fracture mechanics type of toughness evaluation would be desirable. However, such testing for strain-rate sensitive materials will often require well-controlled tensile loading in a time of the order of 1 millisec as well as good control of crack size and of the crack-border sharpness condition. At present the primary handicap on K_{Ic}-measurements is the fact that good control of loading limits us to rather small size specimens. This, in turn, restricts the range of crack toughness which can be investigated.

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References

1 First Report of a Special ASTM Committee on Fracture Testing of High Strength Materials, ASTM Bulletin, January, 1960.

2 G. R. Irwin, "Relation of Crack Toughness Measurements to Practical Applications," *Welding Journal*, Res. Suppl., November, 1962.

3 Fifth Report of Special ASTM Committee on Fracture Testing of High Strength Materials, Materials Research and Standards (forthcoming).

4 J. M. Krafft and A. M. Sullivan, "Effects of Speed and Temperature on Crack Toughness and Yield Strength in Mild Steel," *ASM Trans.*, vol. 56, no. 1, 1963, p. 160.

5 R. W. Boyle, A. M. Sullivan, and J. M. Krafft, "Determination of Plane Strain Fracture Toughness With Sharply Notched Sheets," *Welding Journal*, vol. 27, no. 9, September, 1962, p. 428.

6 J. M. Krafft, "Correlation of Plane Strain Crack Toughness With Strain Hardening Characteristics of a Low—a Medium—and a High-Strength Steel," *Applied Materials Research* (forthcoming).

7 G. R. Irwin and J. E. Srawley, "Progress in the Development of Crack Toughness Fracture Tests," *Materialprüfung*, vol. 4, no. 1, January, 1962, p. 1.

8 H. L. Smith, J. A. Kies, and G. R. Irwin, "Fracture Toughness of Materials for Aircraft and Missiles," ONR Symposium—Materials Research in the Navy (March, 1959), ONR-5, vol. II, p. 475.

9 I. Wolock and C. Fowlkes, "NRL Report in preparation."

10 F. J. Feely, M. S. Northrup, S. R. Kleppe, and M. Gensamer, "Studies on the Brittle Failure of Tankage Steel Plates," *Welding Journal*, vol. 34, December, 1955, p. 596.

11 A. A. Wells, "Strain Energy Release Rates for Fractures Caused by Wedge Action," NRL Report 4705 (March, 1956).

12 G. M. Orner and C. E. Hartbower, "Sheet Fracture Toughness Evaluated by Impact and Slow Bend," *Welding Journal*, Research Suppl. (September, 1961).

13 W. S. Pellini and P. P. Puzak, "Fracture Analysis Diagram Procedures for the Fracture-Safe Engineering Design of Steel Structures," NRL Report 5920, (March, 1963).

14 G. R. Irwin, "Fracture Mode Transition for a Crack Traversing a Plate," Journal of Basic Engineering, Trans. ASME, Series D, vol. 82, no. 2, 1960, p. 417.

15 G. R. Irwin, "Fracture," Springer, *Encyclopedia of Physics*, vol. VI, 1958, pp. 551–590.

DISCUSSION

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The author is to be commended on presenting a fine paper dealing with a most complex subject. The practical as well as the theoretical importance of this work will be readily discernable, if it is realized that 90 percent of the metals used in structures fall in the class of strain-rate sensitive materials. Failures of welded Liberty Ships, tankers, gas transmission lines, and gas storage tanks have pointed out the need for a realistic approach to study the fracture behavior of these materials.

The concept of the stationary crack border with the accompanying build up of a very large plastic zone followed by abrupt crack propagation is indeed an intriguing idea. Similar type behavior has been observed in strain-rate insensitive materials having machined blunt notches. For example, data for $^1/_{16}$-in. thick 7075-T6 edge notched specimens with variable root radii show that for root radii larger than a critical value a decrease in slow crack extension with increasing root radius as evidenced by ink staining, was observed [16]. This behavior is consistent with the crack blunting due to strain-rate sensitivity described by Dr. Irwin.

The minimum value of fracture toughness observed at the adiabatic-isothermal boundary is reminiscent of the adiabitic shear instability observed in ballistic tests. Similar behavior has been observed in the failure of compression tests of tempered martensites as described by Read, Markus, and McCaughey [17].

Additional References

16 J. H. Mulherin, D. F. Armiento, and H. Markus, "The Relationship Between Fracture Toughness and Stress Concentration Factors for Several High-Strength Aluminum Alloys," ASME Winter Annual Meeting, November, 1963.

17 T. A. Read, H. Markus, and J. H. McCaughey, "Fracturing of Metals," *American Society of Metals*, 1948, p. 288.

Author's Closure

The author is grateful to Mr. Carman for directing attention to two pertinent and useful publications from Frankford Arsenal. The paper by Read and others is quite helpful relative to the correlation between K_{Ic} and strain-hardening. In the paper the author calculated the conditions for a shift from isothermal to adiabatic behavior on the basis of the length factor $2r_Y$. Other smaller length factors may prove more useful for this purpose, for example, Krafft's length factor d_T for the development of a plastic strain equal to the strain-hardening exponent, or an estimate of the plastic opening displacement at the crack border.

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